

Quantum Theory and Spacelike Measurements¹

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Abstract

Experimentally observed violations of Bell inequalities rule out local realistic theories. Consequently, the quantum state vector becomes a strong candidate for providing an objective picture of reality. However, such an ontological view of quantum theory faces difficulties when spacelike measurements on entangled states have to be described, because time ordering of spacelike events can change under Lorentz-Poincaré transformations. In the present paper it is shown that a necessary condition for consistency is to require state vector reduction on the backward light-cone. A fresh approach to the quantum measurement problem appears feasible within such a framework.

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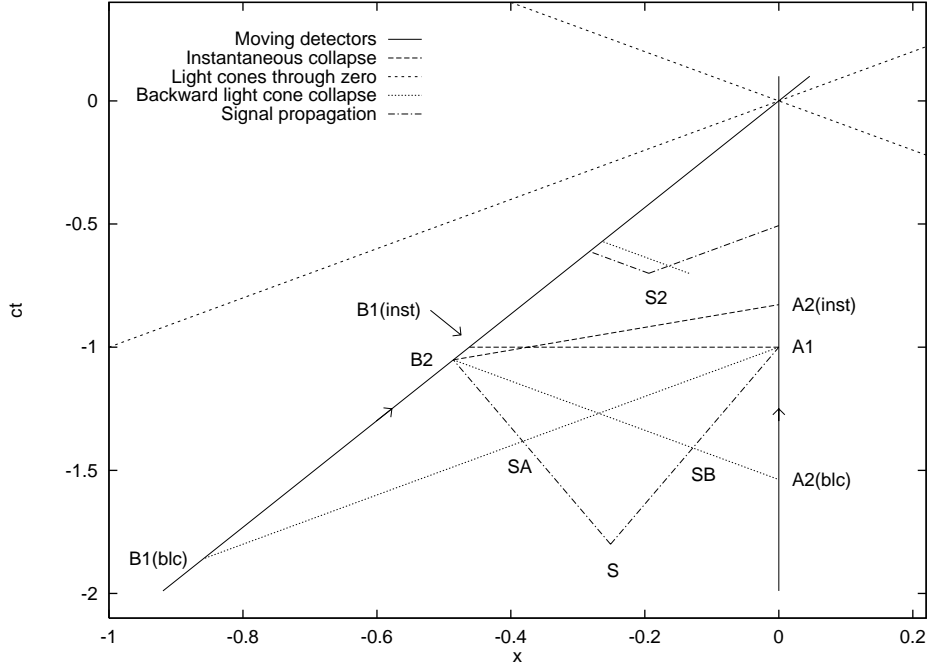


Figure 1: Illustration of the collapse problem.

In a classical, relativistic theory all actions propagate at or below the speed of light. Only timelike (possibly including the limit of lightlike) events can influence one another. Correlations of two spacelike measurements A and B are only possible through some source S in their joint, timelike past. A scenario of this type is depicted in figure 1, where the signal from S reaches detector A at point $A1$ and detector B at point $B2$. Each signal branch is supposed to propagate locally, governed by the appropriate causal, relativistic wave equation.

Quantum correlations between such spacelike measurements are still caused by a source in their common timelike past, but it can be ruled out that the required information propagates at or below the speed of light. First in this paper, we shall briefly review this issue. Afterwards we focus on an ontological view of Quantum Theory (QT) in which the state vector is considered to provide a picture of objective reality and information can propagate on spacelike hyperplanes through reduction (or collapse) of the state vector when measurements are performed. The problem of such an ontological understanding of QT is to find a consistent, explicit prescription for spacelike measurements on entangled states. It turns out that there is the unique implication already described in the abstract, state vector reduction

has to happen on the backward light-cone (blc), which we shall discuss in some details. To have an ontological formulation of QT at hand may be of importance for developing a future theory of quantum measurement.

By now it has become textbook material, see for instance [1], that QT implies correlations between spacelike measurements, which cannot be explained through local propagation at or below the speed of light. An often discussed arrangement is that of a singlet state which decays into two spin 1/2 particles, whose spins are measured at spacelike separations: with respect to direction \hat{a} by detector A and with respect to direction \hat{b} by detector B . The result of each measurement is either +1 for spin up or -1 for spin down, up or down with respect to the chosen direction. In the following we assume that each detector has a well-defined rest-frame and, to begin with, that both detectors are at rest with respect to one another.

First, let both axis be the z -direction: $\hat{a} = \hat{b} = \hat{e}_3$. The +1 measurement by detector A implies the -1 measurement by detector B and vice versa. This correlation is not at all surprising as it is classical one: When the head of a coin is send in one direction and the the tail in the other, precisely the same result is achieved. Can now all measured, spacelike spin-spin correlation be explained this way?

To discuss this question, let us suppose that each detector is constructed to choose randomly, for instance with uniform probability, one out of a discrete number of directions \hat{x}_i , labelled by $i = 1, \dots, n$, and then performs the spin measurement with respect to that axis. Hence, the delivered result is one out of $2n$ mutually exclusive *alternatives*: choice of direction and spin either +1 or -1 with respect to this direction. We denote these alternatives by

$$a^i, i = \pm 1, \dots, \pm n \text{ and } b^i, i = \pm 1, \dots, \pm n, \quad (1)$$

where $a^i, i \geq 1$ denotes the spin +1 measurement by detector A with respect to direction \hat{x}_i and $a^{-i}, i \geq 1$ the spin -1 measurement by detector A with respect to direction \hat{x}_i . The b^i have the same meaning, but for detector B . Let us introduce corresponding probabilities

$$p_A^i, i = \pm 1, \dots, \pm n \text{ and } p_B^i, i = \pm 1, \dots, \pm n, \quad (2)$$

where p_A^i is the probability that detector A picks event a^i and p_B^i the probability that detector B picks b^i . To simplify the arguments we neglect finite extensions of the detectors and assume the detectors to be perfect, what means each set of probabilities is normalized to one: $\sum_i p_A^i = \sum_i p_B^i = 1$. Let \vec{x}_A be the position of detector A and \vec{x}_B of detector B with respect to their common rest frame. The measurement process is said to be spacelike when conditions are arranged as follows: A makes its measurement decision, say a^k , in the time interval $[t_A, t_A + \Delta t_A], \Delta t_A > 0$ and B makes its decision in the time interval $[t_B, t_B + \Delta t_B], \Delta t_B > 0$, such that

$$c(\max[t_A + \Delta t_A, t_B + \Delta t_B] - \min[t_A, t_B]) < |\vec{x}_B - \vec{x}_A|, \quad (3)$$

where c is the speed at light. In words, there is no way of communicating results from A to B at (or below) the speed of light. Hence, an interpretation of the spin-spin measurements as classical correlation implies that a space-time-independent assignment of constant probabilities p_A^i, p_B^i has to exist, which reproduces the observed results. Restrictions on the sets of such probabilities follow from the possibility that both detectors may pick the same direction $i \geq 1$. Then event a^i measured by A implies that b^{-i} is measured with *certainty* by B or vice versa. Implications are, for instance,

$$p_A^i p_A^{-i} = p_B^i p_B^{-i} = 0 \quad \text{and} \quad p_A^i = 0 \iff p_B^{-i} = 0 \quad \text{for} \quad i = \pm 1, \dots, \pm n$$

It was shown by Bell [2] that such constraints lead to inequalities which violate QT predictions. Subsequently, many experiments were performed. They showed violations of Bell's inequalities and confirmed QT. The first results, which actually achieved spacelike measurements, seem to be those of ref. [3]. Recent experiments [4] relate to Franson's [5] realization of Bell's inequality. Our emphasize is on the fact that an interpretation of spacelike measurements as a classical correlation between pre-defined probabilities (2) is excluded, see ref. [6] for a particularly strong example and ref. [7] for pedagogical reviews, which inspired some of our notation.

It appears now natural, see for instance [8], to take the quantum state vector as substitute

for the lost classical reality. To investigate whether (and in what sense) we may attribute reality to quantum states, let us define the probabilities (2) as expectation values calculated from the QT state $|\Psi_S\rangle$, which describes the system before measurement has taken place (the subscript S refers to the source and is omitted when we refer to the QT state after measurement). In our example

$$p_A^{\pm i} = \left| \langle \Psi_A^{\pm i} | \Psi_S \rangle \right|^2 \quad \text{and} \quad p_B^{\pm i} = \left| \langle \Psi_B^{\pm i} | \Psi_S \rangle \right|^2 \quad \text{for } i = 1, 2, \dots, n. \quad (4)$$

Here $i = 1, \dots, n$ labels the axis and $|\Psi_A^{\pm i}\rangle, |\Psi_B^{\pm i}\rangle$ are the eigenfunctions of suitable operators $\mathcal{A}^i, \mathcal{B}^i$. To enter the next level of arguments, let us assume that detector B makes its measurement first [9], in the time interval $[t_B, t_B + \Delta t_B]$, $\Delta t_B > 0$ and, subsequently, A proceeds in the time interval $[t_A, t_A + \Delta t_A]$, $\Delta t_A > 0$, such that $t_A > t_B + \Delta t_B$ holds and the assumption that the measurements are spacelike translates into $c(t_A + \Delta t_A - t_B) < |\vec{x}_A - \vec{x}_B|$. Assume the measurement result of detector B is b^k , $k = \pm 1, \dots, \pm n$. This transforms the state vector $|\Psi_S\rangle$ according to

$$|\Psi_S\rangle \rightarrow |\Psi_B^k\rangle \quad (5)$$

resulting in new probabilities for A , namely

$$p_A^{\pm i} \rightarrow p_A^{\pm i, k} = \left| \langle \Psi_A^{\pm i} | \Psi_B^k \rangle \right|^2 \quad \text{for } i = 1, \dots, n; \quad k = \pm 1, \dots, \pm n. \quad (6)$$

To deliver consistent results, A has to act according to the result of (5) at (or before) some time $t \leq t_A + \Delta t_A$. Experimentally it has been confirmed [3, 4] that A does so indeed. To proceed with an ontological description of QT which attributes reality to the state vector (before as well as after measurement), we have to demand that in coordinate space the wave function collapse

$$\langle \{x\} | \Psi_S \rangle = \psi_S(\{x\}) \rightarrow \psi_B^k(\{x\}) = \langle \{x\} | \Psi_B^k \rangle \quad (7)$$

happens for $x = (ct, \vec{x})$ on a spacelike hypersurface. For simplicity we consider in the following only flat planes as hypersurfaces. In (7) the symbolic notation $\{x\}$ indicates that coordinates of several degrees of freedom may be involved. We assume that the collapse hypersurface is the same for each degree of freedom.

It is believed that there will be no change in observing the probabilities (6) when the distance $|\vec{x}_A - \vec{x}_B|$ becomes arbitrarily large, e.g. covers astrophysical dimensions. We are therefore tempted [10] to regard the rest frame of a detector as preferred and to conjecture that the transformation (7) happens on the instantaneous hyperplane of this frame, *i.e.* is propagated by B at infinite speed at some sharp time $\bar{t}_B \in [t_B, t_B + \Delta t_B]$. The requirement of a *sharp decision time* \bar{t}_B is necessary to get consistent results for the general spacelike situation (3), *i.e.* after relaxing our present condition $t_A > t_B + \Delta t_B$. Of course, the detector should need a finite response time $(\bar{t}_B - t_B) > 0$ for getting to its decision and, afterwards, another $(t_B + \Delta t_B - \bar{t}_B) > 0$ for recording the result, such that only after time $t_B + \Delta t_B$ it is ready to work on its next decision process. In the same way the detector A is supposed to make its decision at time \bar{t}_A . By locating the decisions at sharp times and assuming that some continuous stochastic process is involved in selecting them, it follows that

$$\text{either } \bar{t}_B < \bar{t}_A \text{ or } \bar{t}_A < \bar{t}_B, \quad (8)$$

whereas the likelihood for $\bar{t}_A = \bar{t}_B$ is zero. In conclusion, when both detectors are at rest an instantaneous transformation (7) does ensure consistent measurements.

For a moving observer the time ordering (8) may become interchanged. This does not yet imply an inconsistency, as we have defined the system of the detector which makes the decision as preferred. But the concept of instantaneous state vector reduction becomes questionable. Let us consider detectors A and B which move with constant velocity with respect to one another, denote the coordinates of the corresponding rest frames by (x^α) and (x'^α) , respectively, and locate the detectors at the origins: A at $\vec{x}_1 = 0$ and B at $\vec{x}'_2 = 0$. Without restricting generality, we can choose the orientation of the frames parallel and such that the relative velocity is along the \hat{e}_1 -axis: $\vec{v} = v\hat{e}_1$. With suitable definitions of the time and \hat{e}_1 -axis zero-points, coordinates in the two frames are related by the Lorentz-Poincaré transformations:

$$x'^0 = +x^0 \cosh(\zeta) - x^1 \sinh(\zeta), \quad (9)$$

$$x'^1 = -x^0 \sinh(\zeta) + x^1 \cosh(\zeta), \quad (10)$$

$$x'^i = x^i + x_{2,0}^i, \quad i = 2, 3. \quad (11)$$

Here ζ is the rapidity variable defined through $\tanh(\zeta) = \beta = v/c$. The position of B in the frame of A is given by

$$\vec{x}_B = -\vec{x}_{B0} + \tanh(\zeta) x^0 \hat{e}_1, \quad \text{where } \vec{x}_{B0} = (0, x_{B0}^2, x_{B0}^3), \quad (12)$$

in particular $x_B^1 = x^0 \tanh(\zeta)$. Assume that A initiates an instantaneous transformation (7) at its time x_{A1}^0 . Then B can be aware of the changed probabilities (6) only at or after its time

$$x_{B1}'^0 = x_{A1}^0 \cosh(\zeta) - x_B^1(x_{A1}^0) \sinh(\zeta) = x_{A1}^0 \frac{\cosh^2(\zeta) - \sinh^2(\zeta)}{\cosh(\zeta)} = \frac{x_{A1}^0}{\cosh(\zeta)}. \quad (13)$$

The inverse transformations of (9), (10) are $x^0 = x'^0 \cosh(\zeta) + x'^1 \sinh(\zeta)$, $x^1 = x'^0 \sinh(\zeta) + x'^1 \cosh(\zeta)$ and the position of A in the frame of B is given by $\vec{x}'_A = \vec{x}_{B0} - \tanh(\zeta) x'^0 \hat{e}_1$, in particular $x_A'^1 = -x'^0 \tanh(\zeta)$. Therefore, when B initiates at its time $x_{B2}'^0$ an instantaneous collapse, then A can be aware of the result only at or after its time

$$x_{A2}^0 = x_{B2}'^0 \cosh(\zeta) + x_A'^1 \sinh(\zeta) = x_{B2}'^0 \frac{\cosh^2(\zeta) - \sinh^2(\zeta)}{\cosh(\zeta)} = \frac{x_{B2}'^0}{\cosh(\zeta)}. \quad (14)$$

The consistency condition to be fulfilled is

$$\text{sign}(x_{A2}^0 - x_{A1}^0) = \text{sign}(x_{B2}'^0 - x_{B1}'^0). \quad (15)$$

Inconsistent is an arrangement like

$$x_{A2}^0 > x_{A1}^0 \quad \text{and} \quad x_{B1}'^0 > x_{B2}'^0, \quad (16)$$

which translates as follows: Using (14), (16)

$$\frac{x_{B2}'^0}{\cosh(\zeta)} = x_{A2}^0 > x_{A1}^0$$

and using (13), (16)

$$\frac{x_{A1}^0}{\cosh^2(\zeta)} = \frac{x_{B1}'^0}{\cosh(\zeta)} > \frac{x_{B2}'^0}{\cosh(\zeta)}.$$

Therefore, a solution of (16) is found for

$$\frac{x_{A1}^0}{\cosh^2(\zeta)} > x_{A1}^0 \iff x_{A1}^0 < 0. \quad (17)$$

The inconsistency (16) exists when the detectors are approaching one another. Independently of the sign of the rapidity ζ this happens for negative time, due to our particular choice of coordinates systems. The arrangement depicted in figure 1 is for $\zeta > 0$ and as seen in the rest-frame of A . A collapse initiated by A at the space-time point $A1$ reaches the B world-line at $B1(inst)$ and a collapse initiated by B at $B2$ reaches the A world-line at $A2(inst)$. The contradictory time ordering comes from the fact that the instantaneous hyperplane of one inertial frame is not instantaneous in another which moves with respect to the first. Therefore, we may well admit all spacelike planes right away. To avoid the inconsistency, we have to demand that the collapse plane of A cuts through the B world-line at a time

$$x_{B1}^0 < x_{B1_{\max}}^0 = x_{A1}^0 \cosh(\zeta) \quad (18)$$

and, symmetrically, that the collapse plane of B cuts through the A world-line at

$$x_{A2}^0 < x_{A2_{\max}}^0 = x_{B2}^0 \cosh(\zeta). \quad (19)$$

Here, by definition, $x_{B1_{\max}}^0$ and $x_{A2_{\max}}^0$ are the largest consistent bounds on the corresponding arrival times for given ζ . The $\cosh(\zeta)$ factor follows by exploiting the symmetry (due to the coordinate definitions) and from the observation $x_{B2}^0 = x_{B1_{\max}}^0$, $x_{A1}^0 = x_{A2_{\max}}^0$. For $x_{A1}^0 < 0$ we find $x_{B1_{\max}}^0 < x_{A1}^0$ and, similarly, $x_{B2}^0 < 0 \Rightarrow x_{A2_{\max}}^0 < x_{B2}^0$, *i.e.* the decision may have to propagate backward in time. This does not necessarily imply contradictions. Indeed, we had already noticed that propagation of the collapse process ought to be spacelike and that comparison of times makes then little sense, because Lorentz transformations allow to change the time order. On the other hand, a timelike propagation backward in time would be inconsistent: The collapse plane would miss the signal world-lines which connect source and detectors as indicated in figure 1. Let us determine the collapse plane corresponding to $x_{B1_{\max}}^0$ of equation (18). The x^1 -coordinate of the position of B at time $x_{B1_{\max}}^0$ is given by

$$x_{B1_{\max}}^1 = \tanh(\zeta) x_{B1_{\max}}^0 = x_{A1}^0 \sinh(\zeta). \quad (20)$$

It follows that for finite ζ the line

$$(x_{A1}^0, x_{A1}^1 = 0) \rightarrow (x_{B1_{\max}}^0, x_{B1_{\max}}^1)$$

is still spacelike:

$$(x_{A1}^0 - x_{B1_{\max}}^0)^2 - (x_{A1}^1 - x_{B1_{\max}}^1)^2 = (x_{A1}^0)^2 \{[1 - \cosh(\zeta)]^2 - \sinh^2(\zeta)\} = (x_{A1}^0)^2 2[1 - \cosh(\zeta)] < 0.$$

As detector A does not know about the rapidity of B (or vice versa). We have to find a collapse plane which ensures (18) and (19) for all finite ζ . From (18) and (20) we notice

$$\lim_{\zeta \rightarrow \infty} \frac{x_{B1_{\max}}^0 - x_{A1}^0}{x_{B1_{\max}}^1 - x_{A1}^1} = \lim_{\zeta \rightarrow \infty} \frac{\cosh(\zeta) - 1}{\sinh(\zeta)} = 1.$$

It follows that the *only* collapse hypersurface, which may ensure consistency for all ζ , is the blc, originating at the space-time point $A1$. Similarly, the blc originating at $B2$ is the only potentially consistent collapse hypersurface when detector B makes the measurement. In summary, we have shown: *Either the collapse hypersurface is the blc or a consistent collapse hypersurface does not exist at all.* In the following we pursue the blc scenario in further details. In particular we address a number of consistency concerns and indicate how to overcome them.

In figure 1 we have drawn the light-cones passing through the origin as well as the relevant part of the blc originating at $A1$ and $B2$. The blc of $A1$ hits the world-line of B at $B1(bl)$ and the blc of $B2$ the world-line of A at $A2(bl)$. Of particular importance are the points SA and SB . At SA the $A1$ blc cuts through the S – $B2$ line after the signal left S , but before it reaches B at $B2$. Similarly, at SB the $B2$ blc cuts through the S – $A1$ line in the proper way. This implies that B will act correctly at $B2$ when A makes the collapse decision at $A1$ and, vice versa, A will act correctly at $A1$ when B makes the collapse decision at $B2$. This assumes an order of measurements which, as has been understood by now, does not necessarily agree with the time ordering of the two measurements in the inertial frame of figure 1. We shall come back to this point, after discussing other issues.

To be definite, let us assume that B actually makes the collapse decision at $B2$. The continuous time evolution of the signal propagating towards $A1$ is then interrupted by the discontinuous transformation (7) which defines new initial conditions in the neighborhood of the point SB indicated in figure 1. Subsequently, causal propagation towards $A1$ continues. A minimal requirement on any ontological formulation of QT appears to demand that each detector will, locally, face only well-defined signals. From the viewpoint of a detector the process is then simple: It acts on whatever signal comes in.

Therefore, when detector A performs now its measurement at $A1$, this cannot be allowed to reset at SA the initial conditions of the signal approaching B at $B2$. The explanation at hand is that the collapse initiated by B at $B2$ has reduced the quantum correlation to a purely classical one. The result of the transformation (7) has to factorize in the form

$$|\Psi_B^k\rangle = |\psi_B^k\rangle |\psi_A^k\rangle \quad (21)$$

such that $\langle x|\psi_A^k\rangle$ propagates along the SB - $A1$ line and the detector A will only act on $|\psi_A^k\rangle$. It is instructive to write down the thus obtained time development of the wave function using the coordinates of figure 1 (*i.e.* the rest frame of A). We use x to characterize the localization behavior along S - $A1$ and correspondingly y along S - $B2$. For $x^0 = y^0 = ct$ we find:

$$\langle y, x|\Psi\rangle = \begin{cases} \langle y, x|\Psi_S\rangle & \text{for } t < t(SB), \\ \langle y|\psi_B\rangle \langle x|\psi_A^k\rangle & \text{for } t(SB) < t < t(B2), \\ \langle y|\psi_B^k\rangle \langle x|\psi_A^k\rangle & \text{for } t(B2) < t < t(A1), \\ \langle y|\psi_B^k\rangle \langle x|\psi_A^l\rangle & \text{for } t(A1) < t. \end{cases} \quad (22)$$

Discontinuous jumps occur at $t(SB)$, $t(B2)$ and $t(A1)$. In between we have continuous, causal time evolution. For the time range $t(SB) < t < t(B2)$ we use the symbol $|\psi_B\rangle$ instead of $|\psi_B^k\rangle$, because the y -coordinate has not yet passed the collapse blc. The ansatz $|\psi_B\rangle \sim {}_A\langle\psi_A^k|\Psi_S\rangle$ gives consistent results and the factor is fixed by requesting proper normalization. A singlet state which decays at S into two distinguishable spin $1/2$ particles may serve as an example. Then [1]

$$|\Psi_S\rangle = 2^{-\frac{1}{2}} \{ |-\rangle_B |+\rangle_A - |+\rangle_B |-\rangle_A \} \quad (23)$$

where the subscripts A, B denote the distinguishable particles as well as the branches on which they move towards the corresponding detectors. The wave functions of equation (22) are now

$$\langle y, x | \Psi_S \rangle = 2^{-\frac{1}{2}} \{ \langle y | - \rangle_B \langle x | + \rangle_A - \langle y | + \rangle_B \langle x | - \rangle_A \}$$

$$\langle y | \psi_B \rangle \langle x | \psi_A^k \rangle = 2^{-\frac{1}{2}} \{ \langle y | - \rangle_B - \langle y | + \rangle_B \} \langle x | a^{-k} \rangle_A$$

$$\langle y | \psi_B^k \rangle \langle x | \psi_A^k \rangle = \langle y | b^k \rangle_B \langle x | a^{-k} \rangle_A$$

$$\langle y | \psi_B^k \rangle \langle x | \psi_A^l \rangle = \langle y | b^k \rangle_B \langle x | a^l \rangle_A$$

where b^k , a^{-k} and a^l indicate measurement results as defined by equation (1). Let us stress that our reduction scenario does not rely on any particular choice of coordinates, because the blc is a geometric object which has the desirable property to stay invariant under Lorentz transformations. The point SB is as physical as the points $B2$ and $A1$ are. The choice of coordinates is secondary. Just one more example, in the rest frame of B (indicated by primed coordinates and, as before, $x'^0 = y'^0 = ct'$) we get, for instance,

$$\langle y', x' | \Psi \rangle = \langle y' | \psi_B \rangle \langle x' | \psi_A^l \rangle \quad \text{for } t'(A1) < t' < t'(B2).$$

This may be compared with the previous result for $t(B2) < t < t(A1)$, just re-iterating the fact that an absolute time does not exist. (The values corresponding to figure 1 are $ct_{A1} = -1$, $ct_{B2} = -1.052$ versus $ct'_{A1} = -1.128$, $ct'_{B2} = -0.933$.)

The case where the signals propagate at the speed of light towards the detectors may be perceived as another difficulty. It is undesirable that the collapse surface cuts through the source. Fortunately, the problem does not really exist, due to the finite detector response times. For lightlike signals, and emphasizing now the response time of detector B , this is illustrated for the source $S2$ in figure 1.

Let us return to the ordering problem for our measurements. QT does not specify such an order and the observable correlations do not depend on it, as spacelike operators \mathcal{A} and \mathcal{B} commute. In our context a specific order is needed to arrive at a complete space-time

picture for the wave function. A surprisingly simple and explicitly Lorentz invariant solution exists. One may define the order by comparing proper times (of the detectors) τ_A and τ_B , which the signals need to propagate from the source (creating the quantum correlation) to the detectors, τ_A from S to $A1$ and τ_B from S to $B2$. Corresponding to figure 1: $c\tau_A = 0.8$ and $c\tau_B = 0.664$. Randomness should be involved when those times overlap within the uncertainties set by the detector response times $\Delta\tau_A$ and $\Delta\tau_B$. By reasons already discussed, the reduction time itself, more precisely the corresponding blc, should be sharp.

Whatever the rule for the order of detector decisions is, it will not imply deviations from *standard* QT. However, an ontological formulation of QT invites to transgress beyond *standard* QT. Naturally, it allows to address problems, eventually with observable consequences, which hardly can be properly addressed otherwise. Namely, the dynamical process of QT has since long [11] been perceived as continuous, causal time evolution, interrupted by discontinuous jumps, called measurements. Measurements are achieved by applying detectors to wave functions. The question whether continuous, causal time evolution of an enlarged wave function, now including the detectors and eventually the environment beyond, will yield consistent results has been an issue of controversial debate [12, 13]. Our ontological QT formulation adds to this. Within its framework the answer becomes explicit: Continuous time evolution and jumps are distinct. Including the detectors in the wave function will, up to minor notational re-arrangements, not change the discontinuous reduction (5),(21) and there is no way that inclusion of detector B in the wave function can lead to a causal explanation of the spontaneous change at SB . Actually, for consistency the detectors should have been included, as the states $|\psi_A\rangle$ and $|\psi_B\rangle$ will obviously be mixed-up with the corresponding measurement devices. Whether our explicit rules reflect reality or not may remain undecidable. However, as long as they cannot be excluded, either by reasons of inconsistency or by experimental facts, the often proclaimed consistency of QT measurements with the time evolution of an enlarged system remains hypothetical and, actually, unlikely.

The theory of reduction (jumps) exist only to the extent that QT makes statistical pre-

dictions for the case when a state vector reduction actually happens. In addition, there are good reasons to believe that the stochastic character of these predictions is of fundamental nature. What is missing in QT, and becomes only in the ontological formulation an obvious incompleteness, is an understanding of the microscopic properties of matter which are responsibly for the ability of detectors [14] to make collapse decisions. We only know that reduction happens before macroscopic superpositions of detectors emerge. But it is certainly not satisfactory to attribute the process to emergent, ad-hoc properties of macroscopic matter. Instead, a search for hereto overlooked new, fundamental properties of microscopic matter seems to be legitimate. The framework presented in this paper allows rather naturally to make heuristic-phenomenological assumptions and work along this line is presented in ref. [15].

In conclusion, the quantum state vector may provide a glimpse of reality. A reality which is clearly very different from the traditional, realistic vision of nature [16]. Essentially, it was the achievement of Bell [2] that the latter is, on experimental grounds, now conclusively ruled out. It seems to be time to move forward, to develop a new view of reality on the basis of QT. The discussion of this paper has been limited to the example depicted in figure 1. Hence, the derived constraints appear to be necessary ingredients of a broader, ontological understanding of QT. Whether a general formulation can be worked out consistently remains to be seen, although the author is optimistic. After all, assuming the existence of reality in form of the state vector provides strong guidance.

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- [14] Here the word detector refers to any conglomerate of matter which has the ability to make collapse decisions. A perception that this ability is limited to man-made detectors or even human observations appears unphysical. The physical assumption is that time

evolution of nature (wave function of the universe) proceeds according to two laws: causal time evolution and reduction. It is not well understood when the latter happens. This makes astrophysical approaches, essentially invoking only the first law, quite questionable.

[15] B.A. Berg, hep-ph/9609232, revised version, January, 1998.

[16] A. Einstein, B. Podolsky and N. Rosen, Phys. Rev. 47 (1935) 777.